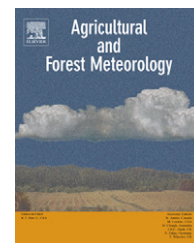


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A mobile platform to constrain regional estimates of evapotranspiration

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ABSTRACT

Regional estimates of evapotranspiration (ET) are needed for environmental analysis and management purposes, yet can be difficult to obtain. Current methods for determining regional ET have spatial, temporal, methodological, and/or logistical limitations that affect their usefulness. To address these gaps, we developed a surface mobile measurement technique, the Regional Evaporative Fraction Energy Balance platform (REFEB), which measures evaporative fraction (EF) and water use efficiency (WUE) using a truck operating on a public right of way. REFEB can measure EF and WUE at 25 or more locations per day, which allows for rapid, dense, and spatially distributed sampling of fields across a region. We assessed the accuracy of the field measurements of EF and WUE with REFEB by comparing them to an Eddy covariance (EC) and Bowen ratio energy balance (BREB) tower. This site validation showed that REFEB has error and uncertainty similar to previous BREB approaches. We then used empirical relationships between field measurements and remote sensing vegetation indices to derive regional maps of EF. We combined these EF maps with satellite observations of net radiation to derive monthly and annual calculations of ET at a 250 m resolution during calendar year 2004 in the Imperial Valley, California, a major agricultural region that is dependent upon irrigation and which has a well constrained water budget. We then summed ET for the Imperial Valley and compared the result to a surface water budget based on irrigation and drainage measurements, which showed good annual and seasonal agreement. These results indicate REFEB produces accurate field measurements of EF and WUE, which can be scaled to estimate regional ET at time scales ranging from less than a week to annual sums.

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1. Introduction

Regional estimates of ET are needed for a variety of ecological, environmental, climatological, and agricultural monitoring and modeling applications. In agriculture, regional ET estimates are critical for managing irrigation supplies and practices to increase agricultural productivity with increasingly scarce water supplies (e.g. Er-Raki et al., 2007; Akbari et al., 2007). Numerous methods exist for determining evapotranspiration (ET) and water use efficiency (WUE);

however, gaps remain in the spatial and temporal range of existing approaches, especially at a regional scale.

Micrometeorological methods such as Eddy covariance (EC) (Law et al., 2002), Bowen ratio energy balance (BREB) (Held et al., 1990), and surface renewal (Paw and Brunet, 1991), use in situ observations that can provide direct, site-specific estimates of ET at high temporal resolution. However, spatial heterogeneity and the relatively few number of sites prevent direct scaling of these calculations to regional estimates. EC can assess regional scale ($\sim 100 \text{ km}^2$) fluxes from an aircraft

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platform at short temporal scales (Barr et al., 1997), but the cost is prohibitive for wide use.

Most approaches to estimating regional ET use a model combined with remote sensing observations and ancillary meteorological measurements. Commonly used semi-empirical models include Priestly–Taylor, Blaney–Criddle, Pruitt–Doorenbos, and Penman–Monteith (Temesgen et al., 2005). These models have been combined with satellite observations of temperature (Kustas et al., 2003), evaporative fraction (Isaac et al., 2004), changes in surface and subsurface water storage (Rodell et al., 2004), and vegetation indices (Cleugh et al., 2007). Regional irrigation networks can estimate ET by applying a model at a network of meteorological sites (Amatya et al., 1995; Temesgen et al., 2005). Depending on the input data, uncertainties arise from errors in approximating model parameters (Rana and Katerji, 1998), estimating necessary parameters from available remote sensing data (Kustas et al., 2003), discrepancies between regional field conditions and the conditions under which the model was developed (Rana and Katerji, 2000), coarse spatial and/or temporal resolution (Rodell et al., 2004) and/or a lack of ancillary meteorological measurements (Rana and Katerji, 2000). Many farmers and irrigation managers use crop specific coefficients (K_c) that estimate field ET based on empirical estimates of reference ET from surface meteorological observations (Temesgen et al., 2005). Regional ET estimates can then be constructed using estimates of reference ET combined with estimates of area averaged K_c derived from land cover estimates (Allen et al., 2005). Accurate estimation of K_c is laborious at a regional scale and requires current surveys of crop acreage and mean planting and harvesting dates, which are often based on extensive ground surveys (Allen et al., 2005). Currently accepted methods such as the FAO-56 protocol (Allen et al., 1998) can overestimate K_c by up to 20% (Allen, 2000).

In this paper, we describe a strategy for assessing regional ET. We developed a mobile micrometeorological measurement technique, the Regional Evaporative Fraction Energy Balance platform (REFEB), which can make point measurements of field evaporative fraction (EF: the fraction of available

surface energy contained in latent heat) and (WUE: here defined as the ratio of instantaneous net carbon uptake over ET) using a truck that operates on public right of ways. REFEB can measure EF and WUE at 25 or more locations per day, which allows for a dense and spatially distributed sampling of fields across a region. We tested REFEB theory against Eddy covariance at an agricultural site in an irrigated region, the Imperial Valley, California (hereafter referred to as “IV”). We then demonstrate an application of REFEB by using it to make field-scale measurements of EF in the IV. Field measurements of EF are regressed against remotely sensed vegetation indices for the fields measured. We then use these empirical relationships to construct regional, medium-resolution (250 m) maps of EF and ET. Finally, we sum these gridded results to calculate regional ET, which we compare to the observed water budget for the entire IV.

2. Methods

2.1. Measurement theory and instrumentation

REFEB combines two established methods, the temperature (T)–specific humidity (q) regression Bowen ratio method (De Bruin et al., 1999) and the Bowen ratio energy balance method (BREB) (Held et al., 1990; Verma and Rosenberg, 1975). The T – q regression Bowen ratio method can be used to assess the Bowen ratio (B : the ratio of sensible heat over latent heat), using high-speed temperature and specific humidity measurements at a single height.

Assuming similarity of transfer coefficients for heat and water vapor, B can be found with Eq. (1), as applied to a T' – q' plot (an example is shown in Fig. 1a). EF can be found through a conversion of B as shown in Eq. (2).

$$B = \gamma \left(\frac{T'}{q'} \right) \quad (1)$$

$$EF = \frac{1}{1 + B} \quad (2)$$

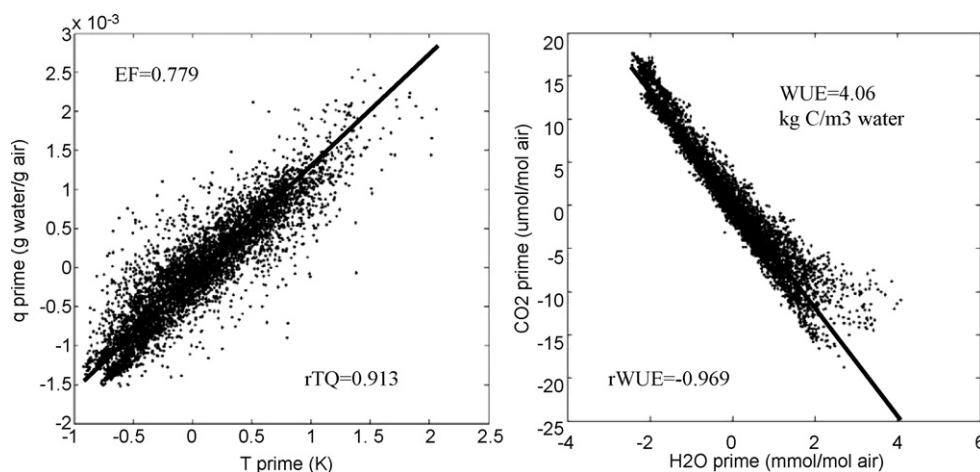


Fig. 1 – Example data plots to illustrate how evaporative fraction and water use efficiency are obtained from raw measurements. Data were recorded at 10 Hz for 10 min downwind of a sudan grass field (location: 32.73736°N, 115.32265°W; time: 18 May 2007 from 9:36 to 10:46 a.m. PDT). (a left) T' – q' plot. (b right) WUE plot of the stop.

where γ is the psychrometric constant found from the specific heat capacity of air (c_p) and latent heat of vaporization (L_v) ($\gamma = c_p L_v^{-1} \approx 4 \times 10^{-4} \text{ K}^{-1}$), q is the specific humidity (in $\text{g H}_2\text{O/g air}$), T is temperature (in Kelvins), and $q' = q - \bar{q}$ and $T' = T - \bar{T}$, where $'$ denotes the fluctuation of the parameter of interest from the mean and $\bar{}$ denotes the mean. \bar{q} and \bar{T} are calculated using a recursive filter with a time constant (τ) of 120 s (Rannik and Vesala, 1999). Similarity of transfer coefficients occurs when the absolute value of correlation between T and q (r_{Tq}) is equal to 1; however De Bruin et al. (1999) found that the T – q regression method is valid when $|r_{Tq}| > 0.25$.

EF can be used to obtain latent heat (LE) fluxes following Eq. (3):

$$\text{LE} = \text{EF} \times \text{AE} = \text{EF} \times (R_n - G) \quad (3)$$

where AE is available energy, R_n is net radiation and G is ground heat flux. ET is then calculated using latent heat of evaporation (λ_E). Due to the similarity of transport of H_2O and CO_2 (Baldocchi, 1994), WUE (Fig. 1b) can be calculated from the mean value of q'/C' , where C' denotes the fluctuation in CO_2 .

REFEB is mounted on a pickup truck and consists of an open path infrared gas analyzer (IRGA) (LI-COR 7500, LI-COR Inc., Lincoln, NE) to measure number density (mmol/m^3) of atmospheric H_2O and CO_2 and atmospheric pressure; a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT) to measure high speed fluctuations of temperature; and a GPS receiver (GPS-18, Garmin Inc., Overland Park, KS) to record position. Data were recorded at 10 Hz with a datalogger (CR1000, Campbell Scientific, Logan UT). Mixing ratios of H_2O and CO_2 are calculated using 10 Hz measurements of atmospheric pressure and air temperature from the CSAT3, using the ideal gas law. The H_2O mixing ratio was converted into specific humidity to calculate EF. All instruments were positioned ~ 2.2 m above the road surface.

2.2. Local evaluation of REFEB

We evaluated REFEB by comparison with a micrometeorological tower at the University of California Desert Research and Extension Center (Desert REC) near El Centro, California, USA (32.812724°N , 115.440538°W , altitude ~ 20 m). The tower was established on a ~ 3 m wide field road between two fields on 12 September 2007. The field immediately west of the tower was 380 m (North–South) by 105 m (East–West) and was planted in sudan grass (*Sorghum vulgare var. sudanense*) from the time of tower establishment until 17 October 2007. The field immediately east of the tower was 380 m (North–South) by 95 m (East–West) and was planted in alfalfa (*Medicago sativa*) in late November 2007. This field was bare at the time of tower establishment. The tower included the same model of open path IRGA and sonic anemometer used by the REFEB, located at the same height (2.2 m) as the truck instruments. Hourly net radiation was measured 900 m southwest of the tower as part of the Meloland station of the California Irrigation Management Information System (CIMIS) also at Desert REC. CIMIS stations are located above well-watered grass surfaces, and their net radiation observations are representative of full cover grass surface. Standard error of CIMIS net radiation is $\sim 20 \text{ W m}^{-2}$ (Temesgen et al., 2007). We calculated ground heat

flux at the site as 10% of net radiation, based on previous measurements of ground heat flux for alfalfa grown in similar climatic conditions in Arizona (Clothier et al., 1986).

We conducted two types of validations using the tower at Desert REC. We compared the REFEB theory against the Eddy covariance method (EC) (Baldocchi, 1994, 2003) by processing the tower's raw measurements with both techniques. We calculated 30-min fluxes from 12 September 2007 until the harvest of the sudan grass field on 17 October 2007. Our tower was located on the eastern edge of the field, and we filtered our data using 1-min averages of wind direction. Flux periods were included if there were no times when the 1-min average direction came from an off field location. We filtered the data using a friction velocity of 0.1 m/s to remove periods of low turbulence, and a Bowen ratio cutoff to remove values less than -0.75 to avoid potentially erroneous REFEB fluxes that can occur when Bowen ratio approaches -1 (Perez et al., 1999).

Our second test compared the truck platform against the tower on 18 and 19 October 2007. This comparison was done to ensure that there was no significant measurement bias introduced by the truck itself. We took a series 10 min measurements over two periods totaling ~ 6 h. The truck was located about 10 m North of the tower on the same North–South field road on which the tower was located.

2.3. Regional study area

The IV's hydrologic budget is very well constrained (Allen et al., 2005), and the region provides an excellent test bed for developing approaches to assess regional ET. Located in the Sonoran Desert between the Salton Sea and U.S.–Mexico border, the IV has a very high potential ET due to the warm climate (annual reference ET as assessed by the California Irrigation Management Information System is ~ 1600 – 1800 mm/year). Average precipitation is very low (~ 75 mm/year). The growing season is year-round, and vegetation is almost entirely dependent on irrigation water coming from the Colorado River via the All-American Canal. Non-irrigated regions in the IV have little or no vegetation. Due to extensive subsurface drains and relatively non-porous soil texture, subsurface flow volume is less than 1% of incoming irrigation water; and relative changes in storage have a small ($< 10\%$) effect on monthly water budget measures of ET (Allen et al., 2005). Virtually all incoming water leaves the IV via ET or by draining to the Salton Sea, mostly through the New and Alamo Rivers. Incoming and outgoing surface water flows are well measured by the Imperial Irrigation District, the U.S. Bureau of Reclamation, and the U.S. Geological Survey (Allen et al., 2005).

2.4. Measurement protocols and campaigns

Measurements were made by parking the truck downwind of a field for 10 min. Wind direction and locations were selected to eliminate contamination from vehicle exhaust or other fields. Measurement locations were selected so that the minimum fetch was greater than 250 m. With the minimal height of the road surface (0–0.5 m) above field surface, and maximum canopy height of ~ 1.5 m, the minimum fetch ensures the footprint falls within the 1:100 height to fetch ratio guideline

(Garratt, 1990). Measurement locations were chosen so that REFEB was within 5 m of the field's edge and there were no large canals or other obstructions between the field and REFEB. We used two quality controls to filter points: wind direction and correlation between temperature and specific humidity. We rejected an observation if $|r_{Tq}| < 0.25$ (De Bruin et al., 1999), or if the Bowen ratio was less than -0.75 (Perez et al., 1999). We also rejected an observation if the wind direction came from an off field location for more than 15 continuous seconds.

2.5. Extrapolating mobile measurements to regional fluxes

We calculated regional ET using the normalized differential vegetation index (NDVI) and the enhanced vegetation index (EVI) independently as proxies for EF. NDVI was used because it is a well-established proxy for vegetation cover and has been previously used in remote-sensing-based estimates of agricultural ET (Gowda et al., 2008). EVI was used because it was designed to eliminate errors found in previous NDVI data sets, including index saturation at high biomass and canopy background and atmospheric influences (Huete et al., 2002). NDVI and EVI were obtained from NASA's MODerate resolution Imaging Spectroradiometer (MODIS) instrument at 16-day, 250 m resolution (MOD13Q1 collection 5). We extracted and plotted the NDVI and EVI values for each field observation against measured EF and applied linear regression to develop empirical curves to predict EF. These curves directly related our 10-min measurements to remote sensing parameters that can be scaled to days and months. We then calculated monthly regional EF by applying these empirical relationships to monthly maps of NDVI and EVI. We calculated monthly NDVI and EVI by averaging the 16-day images that covered the selected month, after weighing each image by the number of days in the month it covered.

To calculate ET from EF, we used regional net radiation observations from NASA's Clouds and the Earth's Radiant Energy System (CERES) Monthly Average Surface Fluxes Product (SRBAVG). SRBAVG provides monthly averages of total-sky net shortwave and longwave radiation at 1-degree spatial resolution (Wielicki et al., 1996). SRBAVG was obtained for every month in 2004. The IV included two CERES pixels, and the pixels were averaged to create a single radiation estimate for the entire IV. CERES derived shortwave and longwave fluxes compare favorably with measurements from the Basic Surface Radiation Network; average biases of CERES for both shortwave and longwave radiation were less than 10 W m^{-2} (Gupta et al., 2004). Because of the monthly averaging, we assumed that ground heat flux was negligible, and that average net radiation equalled the total available energy (AE) (Cleugh et al., 2007).

We chose a monthly time scale out of necessity; it was the shortest time scale for both the CERES regional net radiation observations and for measurements of incoming irrigation water necessary for validation (see Section 2.6). In principle, our approach could be used at weekly and daily time scales if radiation and remotely sensed vegetation data with sufficient temporal resolution were available.

2.6. Comparison of REFEB to regional hydrologic budget

The hydrologic budget for 2004 has three inputs: incoming flow to the Imperial Irrigation District via the All-American Canal (U.S. Bureau of Reclamation, 2006), incoming stream flow on the New River from Mexico (U.S. Geological Survey gauge number 10255550), and rainfall. Monthly rainfall measurements come from the El Centro 2 reporting station (Station ID: 042713) and are screened by the Western Regional Climate Center. We assumed rainfall was constant across the IV.

The hydrologic budget has four outputs: ET, flow from the New River, Alamo River, and direct irrigation drains into the Salton Sea. Stream flow for the Alamo River (gauge number 10254730) and New River (gauge number 10255550) were obtained from U.S. Geological Survey gauges near the Salton Sea. Part of the Alamo River watershed is in Mexico, but over 99% of its flow is irrigation tail water from IV agriculture (California Department of Water Resources, 2006), and its near mouth stream flow is assumed to come entirely from the IV. Measurements on the direct irrigation drains into the Salton Sea are not readily available. The California Department of Water Resources (2006) reported the direct drain flow into the Salton Sea is 10% of the total IV flow into the Sea. We therefore assumed that the remaining 90% of the IV flow came solely from the New and Alamo Rivers and scaled the direct drain flow as a function of the New and Alamo River flow. Our water budget ET was calculated as a residual of the hydrologic inputs minus the three non-ET outputs.

We assumed subsurface flow and change in monthly and annual storage was negligible, following Allen et al. (2005). Allen et al. (2005) found that their method for calculating the water storage term changed monthly water balance $ET < 10\%$ and likely overestimated the storage term. Based on this work, we believe that including the storage term is not critical to our water budget. On an annual basis, uncertainty in the monthly water budget without storage changes was $\sim \pm 6\%$, and was 10–20% with uncertainty in storage (Allen et al., 2005).

3. Results

3.1. Local evaluation of REFEB

We obtained 112 valid half-hour fluxes using the EC method at the Desert REC tower. Prevailing winds came from the west, and all half-hour fluxes measured the sudan grass field. LE measured by REFEB was well correlated with EC, though the REFEB estimates were consistently higher than EC (Fig. 2a). WUE from REFEB was also well correlated with EC (Fig. 2b). There was better agreement between the two methods with respect to WUE than with LE as assessed by the slope of the regression line and the coefficient of determination. We compared the available energy used in the REFEB method to the available energy calculated by EC (Fig. 2c) to see if there was a lack of closure similar to ones observed in previous studies (e.g. Brotzge and Crawford, 2003; Wilson et al., 2002). EC consistently underestimated the available energy compared to REFEB, and average closure with EC was 87% of available energy at the validation site.

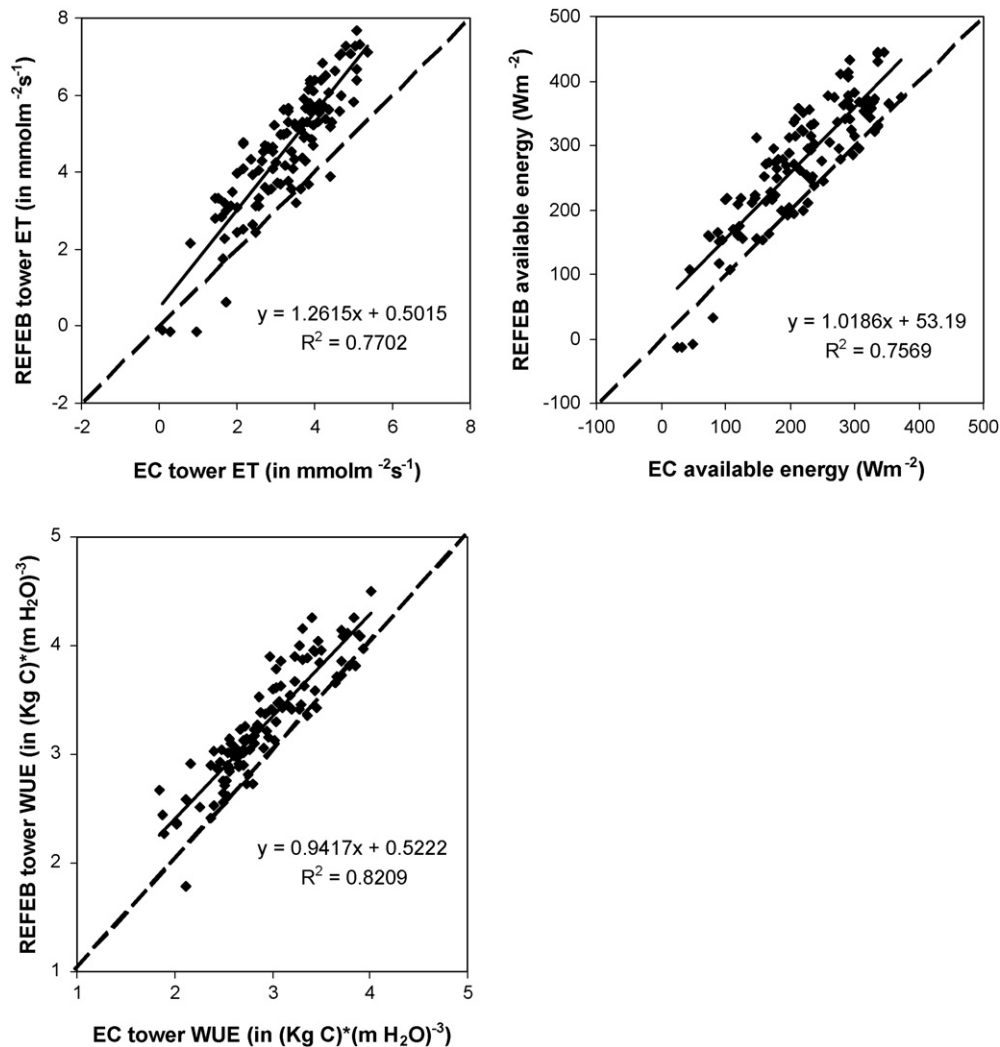


Fig. 2 – Validation data from filtered half-hour periods from 12 September to 19 October 2007 at the Desert REC tower site. The dashed line indicates the 1:1 slope, while the solid line is the linear regression. (a top left) Comparison of REFEB and EC for calculating LE. (b lower left) Comparison of WUE as calculated by REFEB. (c upper right) Comparison of available energy as calculated by the REFEB and EC methods. Available energy from REFEB is calculated as 90% of the net radiation observation from the Meloland CIMIS station located on a nearby field at the Desert REC. As the REFEB method forces energy budget closure, both the total amount of available energy and the ET are higher with the REFEB method compared to the EC method.

EF measured by REFEB was well correlated with the tower measurements using the REFEB theory (Fig. 3). The slope of the regression was within 10% of 1, and the r^2 value between the truck and tower measurements was greater than 0.95. The difference in measured EF between the truck and tower platforms was not significant with a paired sample t-test. The small differences between the truck and tower are likely due to the random measurement errors that are observed in micrometeorological measurements, including nearby towers in the same ecosystem (Richardson et al., 2006). This validation increases our confidence that the truck does not bias the REFEB measurements.

We also assessed the diurnal variation in EF at the Desert REC field site to evaluate the impact of time of day on our regional regression between NDVI/EVI and EF (see Sections 3.3

and 4.3). We took the measurements used in the field validation and binned them by time of day. We then calculated the mean and confidence interval of the EF for each half hour of the day for which we had multiple measurements (Fig. 4). Early morning measurements before 9:30 a.m. showed a higher EF, but from 9:30 a.m. onwards, measured EF did not change significantly.

3.2. Measurement campaigns

We conducted field campaigns from 16 to 18 May and 17 to 19 October 2007 in the Imperial Valley (IV). We made a total of 72 field measurements of EF throughout the IV. We made measurements in multiple land cover types, including desert, fallow field, alfalfa, cotton, hay (klein grass and bermuda

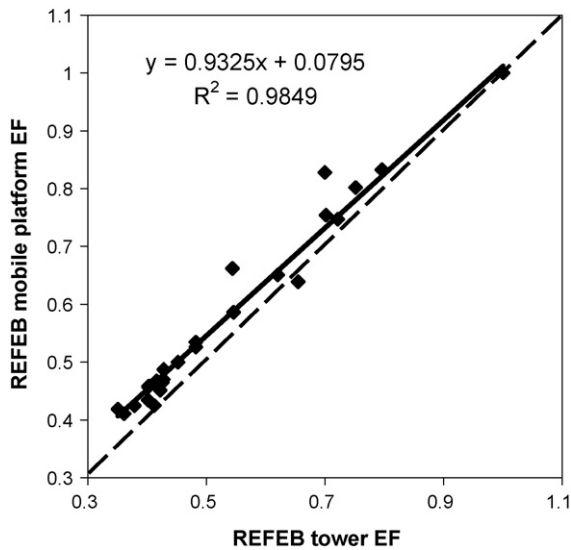


Fig. 3 – Comparison of EF values as measured by REFEB and the tower using REFEB theory during 10-min periods over 6 h on 18 and 19 October 2007. The dotted line indicates the 1:1 ratio. The truck and tower were within 10 m of each other during this intercomparison.

grass), lettuce, onion, sudan grass, salt marsh, sugar beets, and triticale. We made measurements at all daylight hours to quantify the variability in daytime EF for a given crop type and to reduce the dependence of our empirical relationships on the time of measurement. We attempted to make measurements

throughout the IV, though our measurement locations were constrained by wind direction, traveling distance, road location and traffic, location of canals and other obstructions.

We obtained 55 valid field measurements of EF from both campaigns. The most commonly measured fields were alfalfa ($n = 16$) and sudan grass ($n = 18$), which constitute the majority of the Imperial Valley land cover (Putnam and Kallenbach, 1997). Most of our measurements were taken on either the western, eastern, or northern periphery of the IV, away from the cities in the IV's center (Fig. 5).

3.3. Empirical relationships between vegetation indices and EF

Both NDVI (Fig. 6b) and EVI (Fig. 6a) were significantly correlated with EF. EF was more sensitive to changes in NDVI than EVI, as indicated by the slope, but the slopes were not significantly different at the 95% confidence level. NDVI was somewhat better correlated with EF than EVI as indicated by the coefficient of determination. There was scatter in measured EF, particularly over full canopy alfalfa and sudan grass fields with the highest vegetation index values. This could be due to potentially greater diurnal variation in the EF for a fully vegetated location. In the afternoon, measured EF values at these locations were sometimes greater than one, thus indicating a negative Bowen ratio due to a negative sensible heat flux. Morning EF values were slightly less than one, indicating a small, but positive, Bowen ratio. This pattern has been observed in other irrigated agricultural regions, and can result from the advection of sensible heat from nearby areas (the Oasis effect) (Todd et al., 2000; Steduto and Hsiao, 1998).

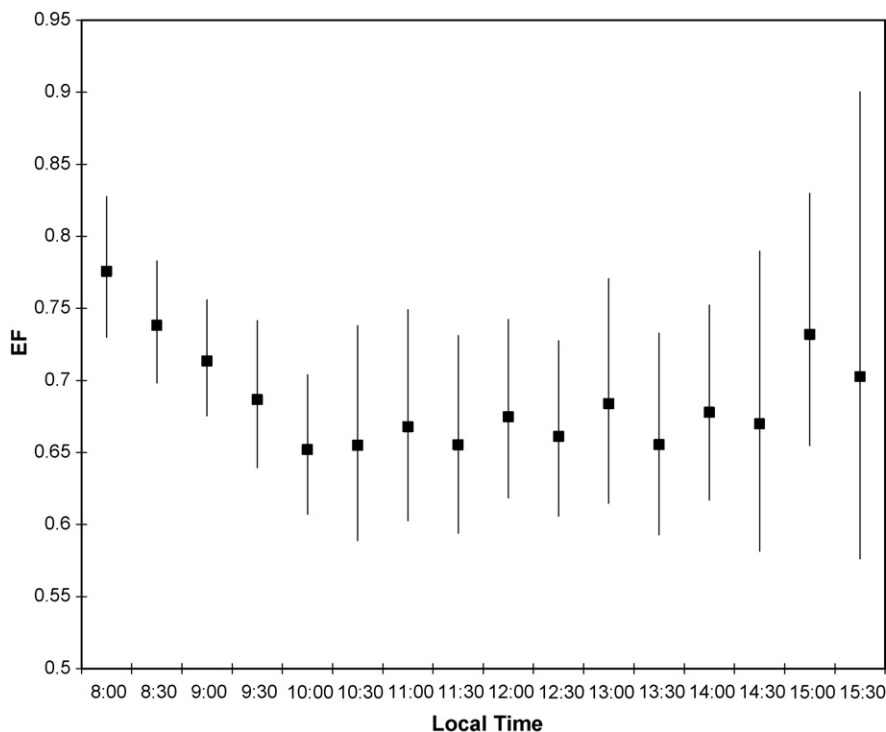


Fig. 4 – Diurnal variation in mean half-hour EF for valid tower fluxes from the tower intercomparison at the Desert REC. Boxes indicate mean EF while lines above and below box show 95% confidence interval of mean EF for the half hour.

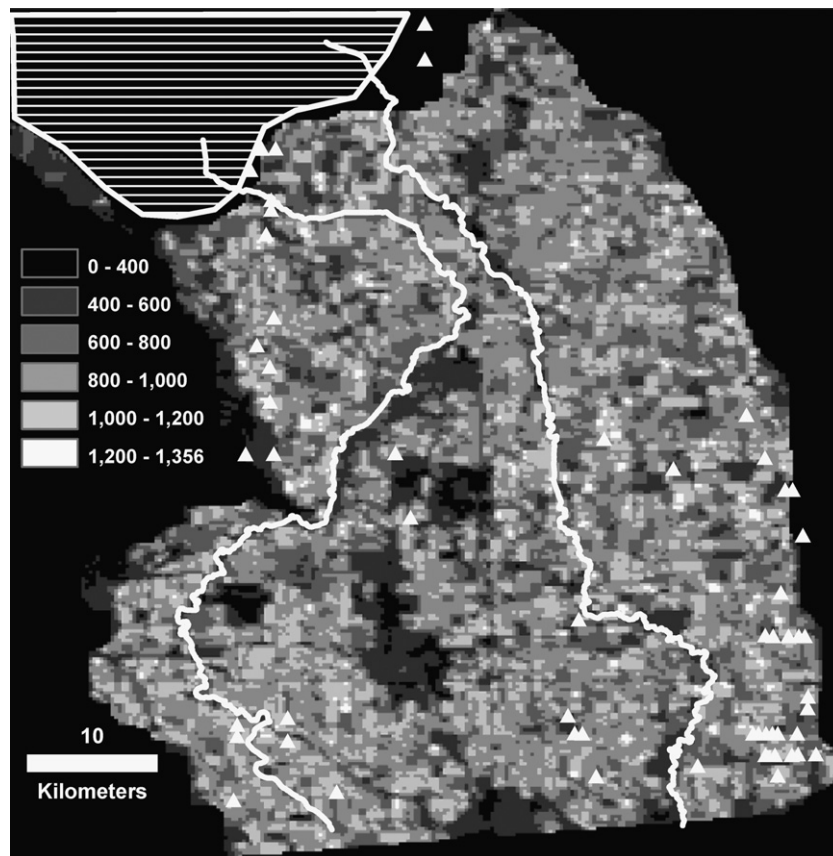


Fig. 5 – Map of year 2004 ET in the Imperial Valley obtained by using the EVI parameterization and CERES radiation. Legend scale is in millimeters/year. The triangles indicate measurement locations used to derive the empirical relationships in Fig. 3. The upper left corner of map is located at (115.827°W, 33.228°N); the lower right corner is at (115.263°W, 32.654°N). Lined area at top of map indicates approximate location of southern portion of the Salton Sea. Dotted white lines show the courses of the New River (left) and Alamo River (right), which extend into the Salton Sea due to the presence of deltas.

3.4. Seasonal pattern of EF and scaling EF to ET using remotely sensed vegetation indices and net radiation

The EF derived from the remote sensing proxies showed a seasonal pattern with the highest EF in the spring and the lowest EF in the summer and fall (Fig. 7). The regional average

EF from NDVI and EVI generally were within 0.05 of each other and ranged from ~0.45 to 0.65. The largest discrepancies between NDVI and EVI occurred during the maximum and minimum EF. The pattern of EF was out of phase with both available energy and ET, and the highest EF coincided with maximum vegetation cover during the months when both

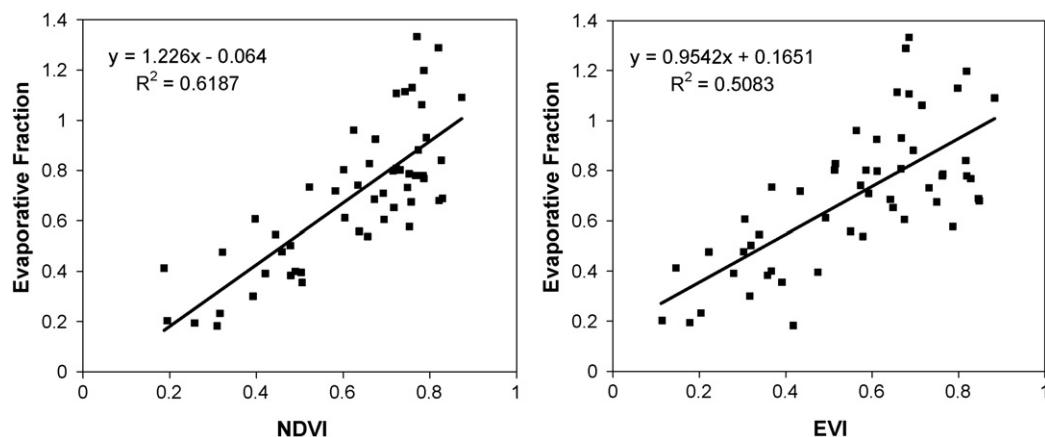


Fig. 6 – Relationships between NDVI and evaporative fraction (EF) (a left) and EVI and EF (b right) during the measurement campaigns in the Imperial Valley.

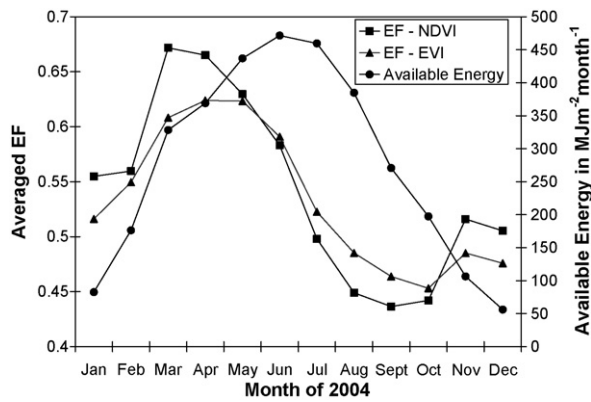


Fig. 7 – (Left y-axis) Area-weighted EF across the Imperial Valley. (Right y-axis) Available energy for the two CERES pixels that cover the Imperial Valley.

winter and summer crops were planted. The summer and fall months had more fallow land, which resulted in the lowest average EF. EF was also out of phase with both available net energy and ET, and the coefficient of variation of EF was substantially less than that for available energy or ET. This implies that seasonal available energy has substantially greater control over ET than seasonal changes in EF.

The monthly calculations of ET using REFEB with NDVI, EVI, and CERES data showed a clear seasonal cycle (Fig. 8). Monthly ET followed the available net energy (Fig. 7). EVI and NDVI curves produced very similar measures of ET; annual sums differed by ~0.5% and monthly sums were always within 10% of each other. Within the IV, annual ET calculated with EVI varied from less than 400 mm/year to about 1350 mm/year (Fig. 5). The highest rates of ET occurred in locations that consistently had high NDVI and EVI throughout the year, thus indicating significant year round agriculture in those pixels. The highest ET values as determined from EVI (>1300 mm/year) compare reasonably well with the reference ET values calculated at the four CIMIS stations in the IV (1500–1800 mm for 2004, see <http://www.cimis.water.ca.gov> for data). Reference ET is a useful comparison because it is measured over a specified well-watered grass surface that grows year round.

3.5. Comparison to surface water budget

The monthly sums of the ET estimates derived from REFEB followed the seasonality of water budget (Fig. 8). Both NDVI and EVI underestimated annual ET by ~16% relative to the water budget (Fig. 8a). The monthly ET calculations followed the same seasonal pattern, with the best agreement during the spring and early summer (March–July). REFEB overestimated ET relative to the budget method in May and June. In January, February, and from August onwards, REFEB underestimated ET relative to the water budget. The largest discrepancies between the REFEB and water budget ET estimates coincided with two events. First, February, August, October, November, and December all had among the largest precipitation totals (>10 mm). Second, the fall months had the largest storage term due to pre-irrigation (Allen et al., 2005). As water storage cannot be accounted for in our budget,

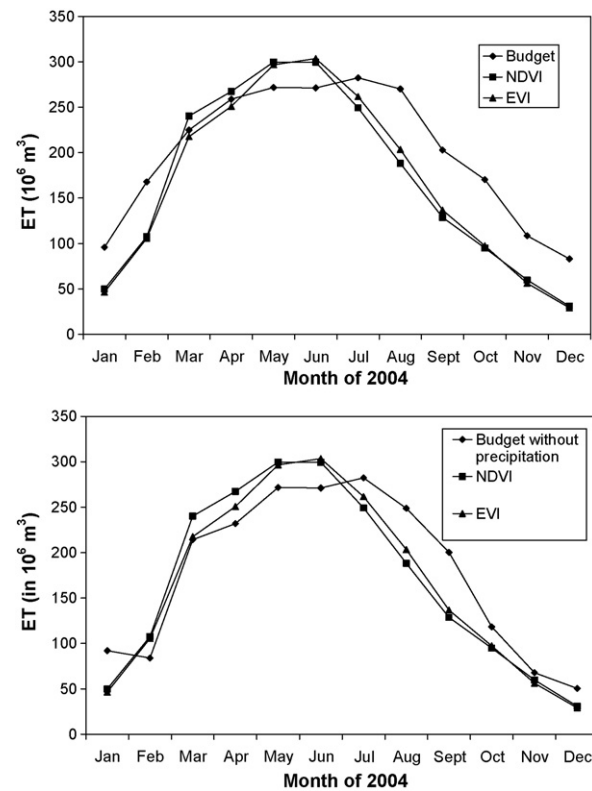


Fig. 8 – Both figures show the REFEB parameterizations compared to two slightly different surface water budget methods. (a top) Budget method used includes precipitation. (b bottom) Budget method used does not include precipitation.

this would likely result in the overestimation of water budget ET during these months.

To test the effect of precipitation on our analysis, we constructed a surface water budget of ET that excluded precipitation as an input (revised budget method). When compared against this revised budget calculation, REFEB underestimated annual ET by ~6%. The seasonal pattern of ET between REFEB and the revised budget method had better agreement (Fig. 8b), with smaller discrepancies than the budget including precipitation. In the first 6 months of 2004, with the exception of January, REFEB overestimated ET relative to the revised budget method. In the latter half of the year, REFEB underestimated the budget method, with the largest underestimations in August and September and smaller discrepancies in November and December. This pattern is consistent with the timing of pre-irrigation in the Imperial Valley.

4. Discussion

4.1. Advantages of REFEB

REFEB has three major advantages not present in current methods. First, REFEB can directly assess surface fluxes rapidly at a network of locations; each measurement takes 10 min,

thus allowing 25 or more locations to be measured per day (Fig. 5). This mobility could reduce errors due to spatial heterogeneity and representativeness present with single site measurements. Second, REFEB is relatively affordable, especially compared to aircraft. The combined cost of all equipment, including pickup truck, is less than 100,000 US Dollars, and it requires only a single technician/driver. Third, the system requires relatively little logistical support. A person can set up REFEB on a vehicle in less than an hour, and measurements can be made from a public right of way. These advantages allow researchers to avoid investing much overhead or setup time to work in a region once REFEB is built.

There are two reasons why Bowen ratio is preferable to EC for a truck-based flux measurement approach. First, the presence of the truck violates a key assumption of EC by distorting the airflow around the truck. This causes persistent positive mean vertical wind flow ($\bar{U}_z > 0$) past the sonic anemometer during measurement periods. However, EC theory states that conservation of mass must be preserved and net advection must be 0, which requires $\bar{U}_z = 0$. Coordinate rotation is often used to force $\bar{U}_z = 0$ over rolling surfaces, but this can be a major source of error (Baldocchi, 2003). More critically, the magnitude of the correction for the truck would be very large relative to the actual surface topography, and trial application of rotation algorithms revealed unrealistically large ET fluxes from the surface (data not shown). A second reason why Bowen ratio is preferable is due to the fact that EC averaging periods must be sufficiently long (usually at least 30 min) to encompass all turbulent fluxes contributing to transport (Baldocchi, 2003). By contrast, 10 min of 10 Hz data provides enough measurements to establish a robust relationship between T and q necessary to calculate EF using REFEB. Assuming valid EC fluxes could be measured from the truck, the 30 min measurement requirement would limit the number of measurements per day, and would likely result in fewer overall measurements and less of the spatial sampling that is the main advantage of REFEB.

4.2. Uncertainties of and errors with REFEB at a field scale

REFEB is subject to the same errors, assumptions, and uncertainties as the previous Bowen ratio type approaches. These include, requirement of similarity of transport of heat, moisture, and other scalars; avoidance of negative Bowen ratios that cause unrealistically large and erroneous fluxes in the Bowen ratio Energy Balance equation, and forced energy budget closure (Todd et al., 2000). Transport similarity is an assumption of both the T - q regression Bowen ratio method, and the more commonly used gradient Bowen ratio (De Bruin et al., 1999). Similarity can be evaluated using the r_{Tq} value (De Bruin et al., 1999), and the requirement is satisfied during most daytime periods while nighttime periods often have stability during which similarity is violated (Perez et al., 1999). To ensure similarity, and thus valid EF and WUE measurements, we apply both our r_{Tq} filter and measure almost exclusively during daylight hours.

A second criterion is avoiding Bowen ratio (B) close to -1 . Perez et al. (1999) found when available energy was significantly greater than 0, $B > -1$ and $B < 0$, the fluxes calculated by BREB were likely valid. Given the large daytime fluxes of

available energy (Fig. 2c), the fact that measured B was always greater than -0.5 at our measurement sites (Fig. 6), and the previous documentation of the Oasis effect, we believe that our measurements where $B < 0$ are valid.

The final uncertainty comes from the forced energy budget closure. Forcing of the energy budget closure results in REFEB-calculated fluxes that exceed the turbulent fluxes calculated by EC (Fig. 2c). Our site has a closure higher than the $\sim 80\%$ average closure reported by Wilson et al. (2002) across the FLUXNET network of EC towers, but lower than the $\sim 95\%$ closure observed by Brotzge and Crawford (2003) across a mesonet in Oklahoma. Foken (2008) found that lack of closure was due to larger scale advection not captured by the EC technique, thus and was larger over short canopy ecosystems such as agricultural fields. Twine et al. (2000) proposed correcting the bias in fluxes measured by EC by using the residual of the energy budget, thus forcing closure similar to that of the BREB method.

4.3. Uncertainties with extrapolating the mobile measurements to regional ET estimates

The small (6%) underestimation by REFEB versus the annual ET with the revised budget method (Fig. 8b) suggests that the relationship between NDVI/EVI and EF is robust, and that vegetation indices are a good predictor of ET in this irrigation-dependent arid region. Nonetheless, two classes of potential errors and uncertainty could affect the REFEB approach to extrapolating mobile EF measurements to regional ET estimates. One class centers on errors in the regression between the vegetation index and EF. One error in this class occurs when there is a spatial mismatch between the footprint of an EF field measurement, and the footprint of a remote sensing pixel. In some cases, the 250 m MODIS pixel used to extract the vegetation index value may contain parts of neighboring fields with more or less vegetation than the footprint of the EF measurement. The high ratio of the average field area in the Imperial Valley (60 to more than 100 ha) to the 250 m MODIS pixel (6.25 ha) likely reduces the impact of this error.

Our NDVI-EF relationship has less scatter than found in previous studies. Wang et al. (2006) found markedly greater scatter in their NDVI-EF relationships in the Southern Great Plains than we did in our relationship. This may reflect the lack of drought stress on well-watered Imperial Valley vegetation. This would result in a tighter coupling between EF and NDVI (Fig. 5a), and fewer pixels with high NDVI/low EF than in a grassland system like the Southern Great Plains, where there is a greater range of water availability for a given NDVI. Future studies in other regions, particularly higher biomass regions, might find that there is a better relationship between EVI and EF due to EVI's enhanced sensitivity. Finally, other remotely sensed vegetation indices (such as the normalized differential water index) can be calculated directly from MODIS surface reflectance (Huete and Didan, 2004), and may provide better empirical predictors of EF, in more drought-stressed regions.

Another source of error is temporal mismatch. An example of this type of error would be if an alfalfa field was cut shortly before the REFEB took an EF measurement. The 16-day MODIS pixel would likely show the higher vegetation index present before cutting due to MODIS' maximum value compositing

algorithm (Huete et al., 2002). A more serious temporal mismatch could be diurnal variation in EF for a particular field. If there was large diurnal variation in EF for a field, our regression could be biased by measurement time of day, especially if a particular type of field was measured more frequently during a particular time of day. However, our assessment of diurnal variation in EF at the Desert REC tower showed there is only minor diurnal variation at our field site after mid-morning (Fig. 4). This consistency in measured EF over the course of the day suggests that the representativeness of our measurements is not overly dependent upon the time of measurement.

A third error caused by the empirical regression could occur when there are surface types that are not well represented in the regression. Our regression relates vegetation indices to EF, and is based on the principle that higher indices reflect dense, vigorously transpiring vegetation in the IV. Situations that result in a wetter surface, but do not result in increase vegetative cover and indices would have an erroneously low ET estimate. Examples of these situations include rain and pre-irrigation. Rain was low (~110 mm in 2004), highly irregular, and would have fallen on soil and plants where the evaporation would not have affected vegetation indices. Pre-irrigation occurs when water is applied to a bare field prior to planting for salinity control purposes, and commonly occurs in the IV in fall before winter planting (Allen et al., 2005). In addition to increasing soil water storage (Section 3.2), pre-irrigation would increase soil evaporation without the corresponding change in vegetation indices.

Spatial and temporal uncertainties might be reduced in future studies if remote sensing observations with higher spatial and temporal resolution are used. A second way to reduce error in the regression is by increasing the number of measurements in a representative way. With an increased sample size, the range of field conditions, crops, time of day, and locations, represented in the vegetation index-EF empirical relationship increases, as does the likelihood that the regression curve is truly representative of mean regional conditions.

4.4. Other potential applications of REFEB

REFEB could be used for ground validation of other model and remote sensing approaches to estimate ET or WUE. Observations from measurement campaigns could be used to constrain parameters for other empirical approaches to estimate ET. For example, if accurate available energy and reference ET estimates are available from a nearby station, REFEB could be used to measure the actual crop coefficient (K_c) and compare it against the literature value from the FAO-56 approach to develop more accurate coefficients under different cropping conditions. Finally, two or more REFEB platforms could be paired together in field scale experimental work. For example, two platforms could make simultaneous measurements of a control or experimental treatment applied to a whole field, or of two different crops at the same time. This would allow the two systems to sample multiple replicates in the same region while controlling for meteorological conditions that have major controls on EF and WUE. We see REFEB

as a complement to current micrometeorological approaches that make field scale measurements. While existing micrometeorological approaches offer a high temporal resolution but a smaller spatial resolution, REFEB offers regional spatial resolution but smaller temporal resolution.

5. Conclusions

The mobile Regional Evaporative Fraction Energy Balance platform (REFEB) is a new technique that can make numerous field scale measurements of EF and WUE. Using a micrometeorological tower, we calculated fluxes using the T-q similarity theory underlying REFEB and the Eddy covariance theory using the same raw measurements. This field scale comparison showed that REFEB followed EC, but has the same energy budget closure issues present with previous Bowen ratio energy balance type approaches. We also demonstrated a new approach to assess regional ET by using REFEB to develop a region-specific, empirical regression curve between remotely sensed vegetation indices and measured EF. Combined with estimates of available energy, we calculated regional ET for a year, and found that it followed monthly ET estimates from a water budget, but underestimated ET by 6–16% relative to the budget.

The REFEB approach provides a complimentary method to current tower-based measurement approaches like EC and the Bowen ratio energy balance. Its strongest aspects are its ability to sample a large number of fields across a region and relative ease of use. Researchers using REFEB need to be cognizant of existing limitations with Bowen ratio type approaches, including footprint issues and unsuitable measurement conditions as well as additional issues of wind direction and stability. Researchers need to be cautious when extrapolating measurements to larger time scales, especially if measurements come from an unrepresentative time frame (such as immediately after a rainfall when crops and soils are excessively wet). However, when properly deployed, REFEB can fill a crucial measurement gap to help constrain regional ET fluxes.

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